A MULTI-FREQUENCY CAMPAIGN ON THE γ-RAY LOUD BLAZAR W COMAE

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Abstract.

We report preliminary results of a multi-frequency campaign on the TeV candidate blazar W Comae (z=0.102). Flux limits by Whipple and HEGRA show that the TeV flux must be considerably below an E^{-2} extrapolation of the EGRET flux. In the framework of proton-initiated cascade models, this seems to imply weak γ-ray attenuation due to pair production in collisions with low-energy photons of the extragalactic infrared background. In a simple SSC model, the γ-ray spectrum cuts off intrinsically just below TeV.

1. Introduction

The window of γ-ray astronomy has been pushed wide open by the CGRO satellite and ground-based Cherenkov light detectors such as Whipple and HEGRA. In the extragalactic domain, EGRET has detected (as of October 1996) 68 blazar-type AGN (Kanbach 1996) at energies of 100 MeV to several GeV. Whipple and HEGRA have so far detected two (three)

blazars at TeV energies. Detections at TeV energies are expected to be rare, since the extragalactic IR background (EIB) attenuates γ-rays by photon-photon pair production, making only the detection of nearby AGN feasible. Gamma-rays of energy E from sources with redshift $z \ll 1$ preferentially produce pairs in collisions with isotropic near-IR photons of energy $\epsilon \approx 0.5\mathrm{eV}/E[\mathrm{TeV}]$. Due to a greater path length, the cutoff in the γ-ray spectrum occurs at lower energies for higher redshift sources. Exact predictions of the expected cutoff are not possible yet, since the shape of the EIB – in contrast to the 3K microwave background – is not well known. Recent predictions of the EIB based on cold and hot dark matter galaxy formation models (MacMinn and Primack 1996) suggest that nearby blazars with z up to ~ 0.1 can be observed at TeV energies and therefore represent suitable probes of the EIB (Mannheim et al. 1996).

TeV observations are also rewarding for tests of blazar emission models. While most of the currently popular models invoke emission from a plasma flowing relativistically from the center of the AGN at small angles towards the observer, the origin of the soft photons scattered into the γ-ray regime by relativistic particles, the distance from the AGN center, and the nature of the relativistic particles in the jet are still a matter of debate. A model that naturally predicts TeV emission was proposed by Mannheim (1993), the so-called proton initiated cascade model (PIC). Here, the jet thrust resides in protons (contrary to other models which use electrons or positrons), and protons and electrons are accelerated in situ, thus avoiding the problem of photon drag in the vicinity of the central engine and the associated overproduction of soft X-rays (Sikora and Madejski 1996).

This paper reports on a multifrequency campaign to observe the EGRET-detected (v. Montigny et al. 1995) BL Lac object W Comae (ON 231, 1219+285). The source has a redshift of 0.102 and we therefore expect it to suffer a cutoff due to attenuation somewhere in the TeV region.

2. Observations

W Comae was observed quasi-simultaneously in February 1996 covering the entire range of the electromagnetic spectrum from GHz to TeV energies. The observatories, observation dates and fluxes are listed in Table 1.

The IUE campaign found W Comae in an active state about two weeks before the bulk of the observations, organised around an EGRET observation. Unfortunately, due to solar angle constraints, UV observations simultaneous with EGRET could not be scheduled. Optical monitoring at Tuorla showed that W Comae was also unusually bright in the optical at that time, whereas the GHz emission did not show enhanced activity. A ToO observation with XTE was performed about a week later, but yielded

Frequency	Instrument	Date	Flux
Radio	Metsähovi (22,37 GHz)	continuous	$S_{22} = 0.67 \pm 0.03$ Jy (27.2) $S_{37} = 0.50 \pm 0.08$ Jy (3.3)
mm	Pic du Midi	Mar.10	$S_{243} = 0.41 \pm 0.04$ Jy
UBVRI V	0.8m McDonald 1.0m Tuorla	Feb.23-Mar.7 Jan 28-Mar.3	$m_{\rm V} = 14.40 \pm 0.08$ (26.2,29.2,2.3) $m_{\rm V} = 13.90 \pm 0.05$ (6.2,10.2)
UV	IUE	Feb.08	$F_{1400} = (3.2 \pm 0.3) \times 10^{-14}\ \frac{\rm ergs}{\rm cm^2\ s\ \AA}$
X-rays	XTE	Feb.17.	$F_{2-10} < (3.5 \pm 1.5) \times 10^{-5}$ Crab
100 MeV	EGRET	Feb.20-Mar.5	$F_{>100} = (19.2 \pm 6.0) \times 10^{-8}\ \frac{\rm photons}{\rm cm^2\ s}$
TeV	Whipple HEGRA	Jan-Feb Feb. 13,16-19,26,27	$F^{3\sigma}_{>0.35} < 7.7 \times 10^{-12}\ \frac{\rm photons}{\rm cm^2\ s}$ $F^{3\sigma}_{>1.0} < 1.05 \times 10^{-11}\ \frac{\rm photons}{\rm cm^2\ s}$ $F^{3\sigma}_{>1.5} < 0.29 \times 10^{-11}\ \frac{\rm photons}{\rm cm^2\ s}$

TABLE 1. Observation log

only an upper limit indicating flux below previously reported levels. The optical campaign at McDonald Observatory showed no signs of extraordinary activity during the EGRET observations[1]. Optical monitoring at Tuorla shows that the flux declined steadily from the time of the IUE observations to the time of the optical/γ-ray effort (see also Tosti et al. 1997). The V-magnitude decreased by $\Delta m_{\rm V} \sim 0.5$ during this time. Our EGRET observations showed that W Comae was weaker than during its strongest detection in November 1993 by a factor of 1.5, resulting in a detection above 100 MeV with just 4.2σ. This weak signal does not allow for a determination of the spectral index. Since most counts were found at energies below 300 MeV, this indicates a steeper spectrum than observed before, i.e. a photon index of 2.0 rather than 1.4 (v. Montigny et al. 1995) or maybe even a peak in the spectrum in this energy range. Only upper limits were derived at TeV energies from HEGRA (Petry et al. 1997) and (preliminary) Whipple data analysis. Rapid blazar variability with outbursts on time scales of days or less has been reported by Wagner and Witzel (1995) and Gaidos et al. (1996). It is difficult to catch such short-duration outbursts in multi-frequency campaigns. Our spectrum shown in Fig.1 av-

[1] Monitoring at McDonald Obseratory was done for all flat-spectrum radio sources in the FOV of EGRET. None of these sources was in an unusually bright optical or γ-ray state during the program. Radio monitoring showed that one source, 1222+216, was in a fairly active state characterised by a rapidly increasing high-frequency radio flux. The source was, however, not within the FOV of EGRET used in the W Comae observation.

erages the emission over a few weeks. The constancy of the radio flux and the only small differences in the optical fluxes between the time of the IUE and EGRET observations make us quite confident that the data represent a realistic snapshot spectrum of W Comae.

3. SSC and PIC models

Bearing in mind the caveats mentioned above, our quasi-simultaneous spectrum shown in Fig.1 constrains emission models.

Let us first consider a very simple SSC model, since it is the most economic one requiring only the observed photons, electrons, and a magnetic field. We adopt the simple picture where the $\alpha \sim 1$ IR-to-UV emission is optically thin synchrotron emission from a homogenous, spherical blob in the jet. We adopt an IR spectral break at $\epsilon_{\mathrm{syn,b}} \sim 0.1$ eV and a UV cutoff at $\epsilon_{\mathrm{syn,c}} \sim 10$ eV, better spectral coverage would be required to determine these energies more precisely. Self-Compton scattering of the synchrotron spectrum produces a wider and more rounded γ-ray spectrum between a smoother γ-ray break energy $\epsilon_{\mathrm{ic,b}} \sim \epsilon_{\mathrm{syn,b}}\gamma_{\mathrm{b}}^2$ and turnover energy $\epsilon_{\mathrm{ic,c}} \sim \epsilon_{\mathrm{syn,c}}\gamma_{\mathrm{c}}^2$. We put $\epsilon_{\mathrm{ic,b}} = 100$ MeV, so that we obtain $\epsilon_{\mathrm{ic,b}}/\epsilon_{\mathrm{syn,b}} = \gamma_{\mathrm{b}}^2 \sim 10^9$ from the above equation. With the formula for the characteristic synchrotron energy $\epsilon_{\mathrm{syn}} \sim \delta(B/B_{\mathrm{c}})\gamma^2 m_{\mathrm{e}}c^2$ where δ denotes the Doppler factor of the jet and $B_{\mathrm{c}} = 4\times10^{13}$ G we obtain an expression for the magnetic field, viz. $B \sim (\epsilon_{\mathrm{syn}}/\delta m_{\mathrm{e}}c^2)B_{\mathrm{c}}\gamma^{-2}$. Inserting $\epsilon_{\mathrm{syn}} = \epsilon_{\mathrm{syn,b}}$ and $\gamma^{-2} = 10^{-9}$ this yields an estimate of the $B \sim 10^{-2}/\delta$ G. The γ-ray turnover in this simple model would be just below $\epsilon_{\mathrm{ic,c}} \sim (\epsilon_{\mathrm{syn,c}}/\epsilon_{\mathrm{syn,b}})^2\epsilon_{\mathrm{ic,b}} \sim 1$ TeV. Thus, within the uncertainties of this simple SSC model, one would expect a rather low magnetic field strength and a γ-ray turnover just below TeV.

By analogy, the PIC model considers radiation induced by protons scattering off the synchrotron photons in the jet. Reaching much higher energies than the electrons, the protons produce synchrotron γ-rays themselves (peak at ~ 100 MeV in Fig.1) and initiate electromagnetic cascades by photo-pair and photo-pion production (bumpy spectrum > 100 MeV). Parameters for the model fit shown in Fig.1 are $\delta_{10} = 3.6$, proton-to-electron cooling rate ratio $\xi = 10^{-3}$ (at resp. maximum energies), proton-to-electron energy density ratio $\eta = 7\eta_{\mathrm{CR}}$ ($\eta_{\mathrm{CR}} = 100$ denotes the value for local cosmic rays), jet opening-angle $\Phi = 2°$, and jet luminosity $L = 8 \times 10^{44}$ ergs s^{-1}. A magnetic field of $B = 37$ G is computed assuming equipartition. External absorption does not have to be strong, but appears to be necessary to avoid a conflict between the predicted flux and the TeV limits. By contrast, the SSC model seems to be consistent with a cutoff just below TeV and therefore does not require any external absorption.

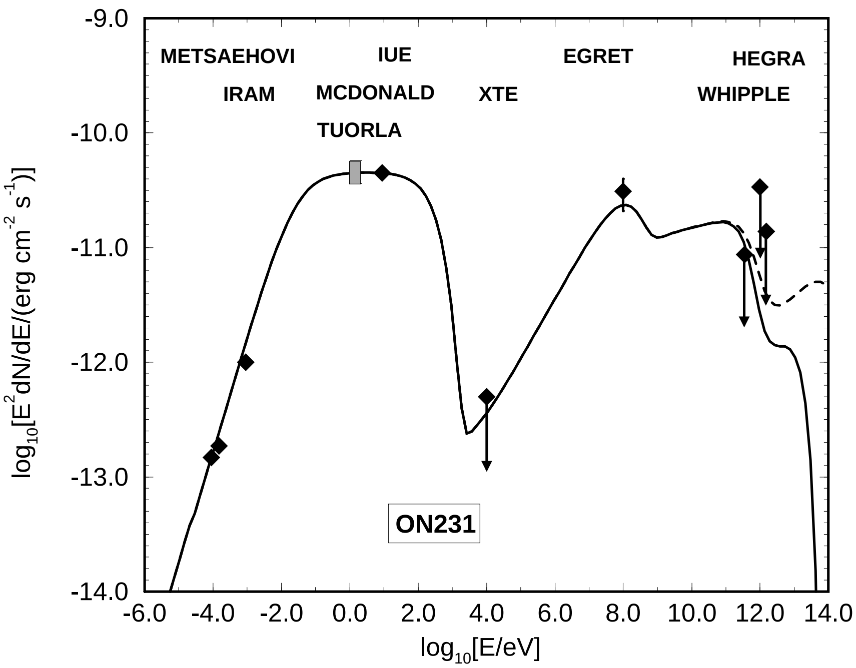

Figure 1. Quasi-simultaneuous multi-frequency spectrum of W Comae during the period February 08 to March 10, 1996. The flux range in the optical indicates the observed variations between the time of the IUE and the EGRET observation. For the XTE flux limit and the differential EGRET flux a photon index of 2, for the TeV limits a photon index of 3 was assumed. The *solid line* shows a proton blazar model fit taking into account external γ-ray absorption (adopting $H_\circ = 75$ km s-1 Mpc^{-1}, $\Omega = 1$, $\Lambda = 0$, and the average EIB model from MacMinn and Primack 1996). The *dashed line* shows the model spectrum without external absorption.

4. Discussion

The γ-ray observations have detected W Comae in a relatively low state of emission. Optical monitoring shows that the source was in decline during the γ-ray observations, supporting the picture of other multifrequency campaigns which found optical through γ-ray emission to be temporally associated. The question remains, however, why it has not been detected by Whipple or HEGRA. Extrapolating from the EGRET flux with an assumed photon index of 2.0, one exceeds the TeV limits, i.e. such a spectrum would have to steepen due to either internal or external absorption. SSC models with rather weak magnetic fields of $B \sim 0.001 - 0.01$ G can explain the HEGRA/Whipple non-detections with W Comae being a member of

the RBL class, which have intrinsically lower cutoffs than XBLs such as Mrk 421 (Maraschi et al. 1996). Detailed modeling will show whether the faintness of W Comae in X-rays is consistent with an SSC explanation of the γ-rays.

The PIC model (Mannheim 1993) predicts an approximate E^{-2} spectrum at EGRET energies and an approximate E^{-3} spectrum at TeV energies. For Mrk421, the >TeV spectrum has indeed been observed to be smooth up to 5-8 TeV and to be steeper than the EGRET spectrum (Petry et al. 1996, Krennrich et al. 1997). This indicates that the cosmic pair-creation optical depth at 5 TeV and $z = 0.03$ is very small. Using a model for the EIB based on the work of MacMinn and Primack (1996), we obtain $\tau_{\gamma\gamma}(z = 0.03, 5 \text{ TeV}) \sim 0.3$ and $\tau_{\gamma\gamma}(z = 0.10, 1 \text{ TeV}) \sim 0.8$. The steepness of the TeV spectrum of W Comae predicted by PIC is not entirely sufficient to reduce the predicted flux below the Whipple flux limit, although such a conclusion may well be changed taking into account the flux variations seen in the optical over the observation campaign. Taking into account the above cosmic optical depth, we obtain marginal agreement of the model fit with the data. Another possibility is that absorption by a warm dusty torus (Protheroe and Biermann 1996) is important.

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